High-precision GNSS Orbit, Clock and EOP Estimation at the United States Naval Observatory

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***Abstract*—The United States Naval Observatory (USNO) produces GPS-based estimates of satellite orbits, satellite- and receiver-clock time corrections, and earth-orientation parameters five times per day: once in a daily "rapid" process, the results of which are available with approximately 16-hour latency, and four times in an every-six-hours "ultra-rapid" process, the results of which are available with 3-hour latency. The rapid products supply 24 hours of post-processed estimates; the ultra-rapid products supply 24 hours of post-processed estimates with 24 hours of predictions. As is, the ultra-rapid products are suited for real-time systems where high-accuracy GPS orbits are required. In addition to providing high precision and low latency, these products are available on an extremely reliable basis. USNO is one of the few DoD providers of these GPS-based estimates and performs duties as an Analysis Center (AC) of the International GNSS Service (IGS).**

Recently, the USNO has begun to test the incorporation of GLONASS observational data into a non-operational "rapids" processing. The resulting solutions from this case study will be compared to a USNO's GPS-based control solution as well as to the combination rapid products produced by the IGS. It is shown that the network stations used in the GLONASS test case have a noticeable improvement in in their position estimate RMS in comparison to the control solution. Performing a 7-parameter Helmert transformation indicates that the Z-direction rotational values appear to have the most improvement from the inclusion of the GLONASS observations.

Keywords-GPS; GNSS; GLONASS; Earth Orientation; Orbit

I. Introduction

The GPS Analysis Division, part of the Earth Orientation Department at the United States Naval Observatory (USNO), produces GPS carrier-phase-based estimates of satellite orbits, satellite- and receiver-clock time corrections, and earth-orientation parameters five times per day in its service as an associate Analysis Center (AC) of the International GNSS Service (IGS) [1]. The processing is conducted using *Bernese 5.0 GPS Analysis Software* [2] in tandem with additional custom pre-processing and automation routines developed in-house.

Two major product sets are submitted daily as part of the service to the IGS. The "rapid" product processing is conducted once per day using measurements collected the previous UTC day. Solutions are obtained using a combination of network and precise point positioning (PPP) [3] algorithms and are available with 16-hour latency. The "ultra-rapid" product processing is conducted 4 times/day using 24 hours of measurement collected for the 24 hours prior to the processing time. The rapid products supply 24 hours of post-processed estimates while the ultra-rapid products supply 24 hours of post-processed estimates plus 24 hours of predictions.

In addition to the rapid and ultra-rapid solutions, the USNO AC produces the IGS final troposphere estimates on a daily basis for over 300 stations in a PPP based method. The USNO also estimates a GPS-carrier-phase based extrapolator of Very Long Baseline Interferometry (VLBI) based UT1-UTC estimates, known as "UTGPS," once/day. Some geophysical/geodetic quantities, which are not submitted to the IGS, are estimated as well including receiver coordinates. All products can be downloaded immediately after completion from the USNO website ftp://maia.usno.navy.mil/GPS/.

The inclusion of the GLONASS data presents an opportunity for expansion and increased flexibility of the operational GPS-based rapids products. The stations which receive both GPS and GLONASS signals could benefit from improved coverage especially for stations in higher latitudes as a result of the higher inclination orbits of the GLONASS satellites (GPS inclination is 55 degrees and GLONASS inclination is 64.8 degrees). This benefit is seen through the increased number of observations per epoch processed. The incorporation of the GLONASS signals would affect stations used in the network solution as well as in the PPP solution of the rapid product processing.

To evaluate these multi-GNSS signal test solutions of the combined processing of the GPS and GLONASS observational data, a comparison to a control version of the USNO GPS-based rapid product will provide insight into the benefits and drawbacks of a multi-GNSS signal based rapid product. This incorporation of a second satellite constellation should yield a basis for what to expect as more GPS-like signals are available for inclusion, such as ESA's GALILEO and China's COMPASS/BeiDou-2. The IGS's rapid product gives a readily available and consistent external source for comparison which allows for determining the quality of the multi-GNSS signal USNO test solutions with respect to the control USNO GPS-based rapid products.

The purpose of this paper is twofold, first to discuss the parameter-estimation capabilities, demonstrated strengths, and the accuracy/precision of estimates of the current USNO

operational GPS-based products submitted to the IGS. Secondly, the incorporation of GLONASS observation test solutions will be presented to explore the potential benefits and drawbacks to processing a multi-GNSS signal based product.

II. Method

A. Operational

The basic processing of the USNO's operational rapid product is conducted once/day with a combination of a network solution and a PPP estimation method using the *Bernese 5.0 GPS Analysis Software* [2]. A 27-hour observation window which covers the entire previous UTC day is used to lessen any day boundary effects on the estimations. The previous IGS ultra-rapid orbits, clocks and Earth orientation parameters are utilized as the a priori inputs. Once the input observation files have been screened and pre-processed, the processing begins with the network solution which uses a subset of the available stations that define the IGS08 reference frame to determine the GPS satellite orbits, the Earth orientation parameters and the corresponding receiver- and satellite-clock time estimates. The remaining available stations are processed separately using the network solution outputs as inputs with a PPP method to estimate the associated receiver clocks and station coordinates. Solutions for approximately 100 clocks are obtained using either network or PPP algorithms and are available with 16-hour latency. The uncertainty of these estimates is evaluated by comparing them to the IGS rapid combination solutions. Since the IGS rapid combination product is formed with the solutions obtained from multiple Analysis Centers (ACs) using various different software packages, the product is largely unbiased to particular software methods or modeling.

B. Multi-GNSS

The basic processing of the multi-GNSS signal test rapid run is almost identical to what is described for the operational GPS-based rapid run. The previous day's IGS GLONASS combination product is used for a priori inputs to the GLONASS test case. The GLONASS signals are used both in the network and PPP portions of the run with the GLONASS satellite orbits and clocks estimated at the same time as the GPS satellites in the network solution. This results in 56 satellites (the full GPS and GLONASS constellations) being used throughout the processing for stations that receive both GPS and GLONASS observations.

The multi-GNSS signal based run is compared to a control version of the USNO GPS-based rapid products (the control solution is not the operational solution sent into the IGS). This control version will be a rapid processing run on the same machine as the multi-GNSS signal rapid processing run. By providing a control rapid run, the variations in software between machines and any processing differences from the operational rapid run will not affect the comparison. The stations that are used in both can be more tightly controlled in this scenario and are set to be identical for the control and multi-GNSS signal processing runs on each day. The comparison to the control rapid solution will give insight into what impacts to the solution to expect from processing multi-GNSS signals. Note that the station baselines for the network solution are determined based on the maximum number of common observations between stations. This can result in a different set of baselines being used in the multi-GNSS signal based run than the control run as a result of the number of observations in stations that receive both GPS and GLONASS signals being increased. Therefore, the control rapid processing and the multi-GNSS signal test processing will naturally be dissimilar.

Finally, each solution will be compared to the IGS rapid combination solution and will give insight into the possible changes in quality to expect from inclusion of GLONASS data into the operational processing. All of the data which follows is for the same 14 day time span (days 054 to 067 for year 2012) to maintain consistency throughout the results and discussion except where noted.

III. Results and Discussion

A. Operational

USNO is one of the few Department of Defense providers of GPS carrier-phase-based estimates. In addition to providing high precision and low latency, these products are available on an extremely reliable basis. Since September 2007, 100% of UTGPS estimates, 1639/1640 of rapid estimates, and 99% of ultra-rapid estimates have been produced/distributed on time.

The current (2011) precision with respect to IGS and IERS estimates are as follows: orbit precision is 1-3 cm post-processed and ~5 cm predicted; clock-estimate precision is ~125 ps post-processed and 2-3 ns predicted. Polar-motion estimate precision is less than 200 microarcsec post-processed and 350-400 microarcsec predicted. Note that Fig. 1 and Fig. 2 illustrate an improvement in the polar motion and clock estimate difference from the IGS values over the course of the year 2011 in both average value as well as variation in polar motion and outliers in clock estimates. Length of Day (LOD) estimates have 10-20 microsec precision. These precision values are for both the rapid and the ultra rapid products. As expected, the rapids are in general more precise and their values fall towards the lower side of the ranges.

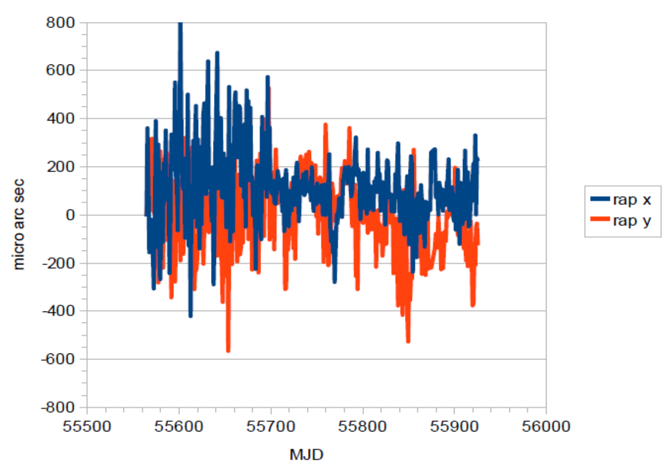

Figure 1. RMS Difference of USNO Operational Rapid Earth Orientation Polar Motion with the IGS Final Polar Motion Solution for Year 2011

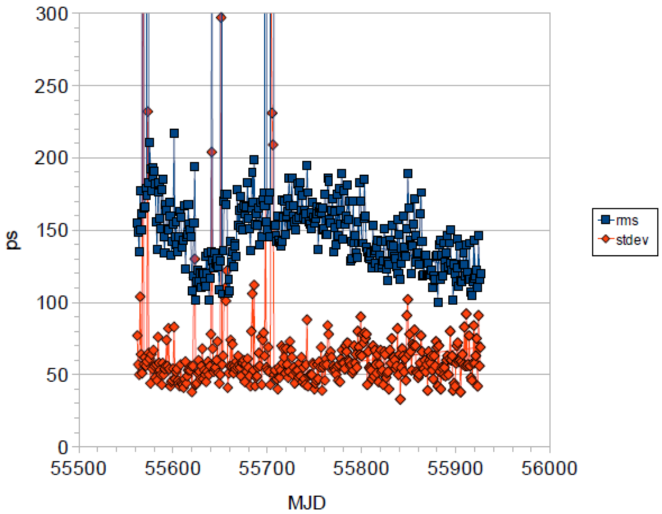

Figure 2. Difference of USNO Operational Rapid Earth Orientation Clock Estimates with the IGS Rapid Clock Solution for Year 2011

Tab. 1 and Tab. 2 give the comparison values for the USNO operational rapid solution with the IGS rapid combination product for the 14-day time span that covers the test data for the multi-GNSS signal solutions. The average rotational value in the Z direction for the Helmert transformation easily stands out.

B. *Multi-GNSS*

A 7-parameter Helmert transformation was performed on both the multi-GNSS test orbits and the control orbits with respect to the IGS rapid combination orbits. In general, the multi-GNSS signal solution appears to slightly improve the average translations as seen in Tab. 3. The standard deviations indicate that the variation is not significantly different than the control case. The rotation values show real improvement in the Z direction with a much lower average and standard deviation. This implies that the inclusion of the GLONASS observations into an operational solution could provide an improvement in the rotation in the Z direction. This is illustrated in Fig. 3 when the Z rotational direction for the multi-GNSS test orbits is mostly consistent with only occasional deviations.

TABLE I. USNO Operational Rapid Orbit Solution Difference with IGS Rapid Combination Product: 7-Parameter Helmert Transformation for Days 054-067 of 2011

	Translation Average [mm]	Translation Std. Dev. [mm]	Rotation Average [µas]	Rotation Std. Dev. [µas]
X	**1.7**	**1.0**	**-3**	**101**
Y	**-1.7**	**1.2**	**29**	**120**
Z	**-0.8**	**1.4**	**166**	**57**

TABLE II. USNO Operational Rapid Solution Difference with IGS Rapid Combination Product: Earth Orientation Parameters for Days 054-067 of 2011

	Average [µas]	Std. Dev. [µas]
Polar Motion X	**-50**	**130**
Polar Motion Y	**63**	**10**

TABLE III. Multi-GNSS signal and Control Rapid Solutions Difference with IGS Rapid Combination Product: Helmert Transformation for Days 054-067 of 2011

	Dir.	Trans. Average [mm]	Trans. Std. Dev. [mm]	Rot. Average [µas]	Rot. Std. Dev. [µas]
Multi.	***X***	**0.6**	**1.5**	**31**	**150**
	Y	**-1.7**	**1.5**	**144**	**193**
	Z	**-0.8**	**2.2**	**44**	**56**
Control	***X***	**0.9**	**1.3**	**18**	**84**
	Y	**-1.9**	**1.5**	**157**	**101**
	Z	**-0.6**	**1.9**	**107**	**104**

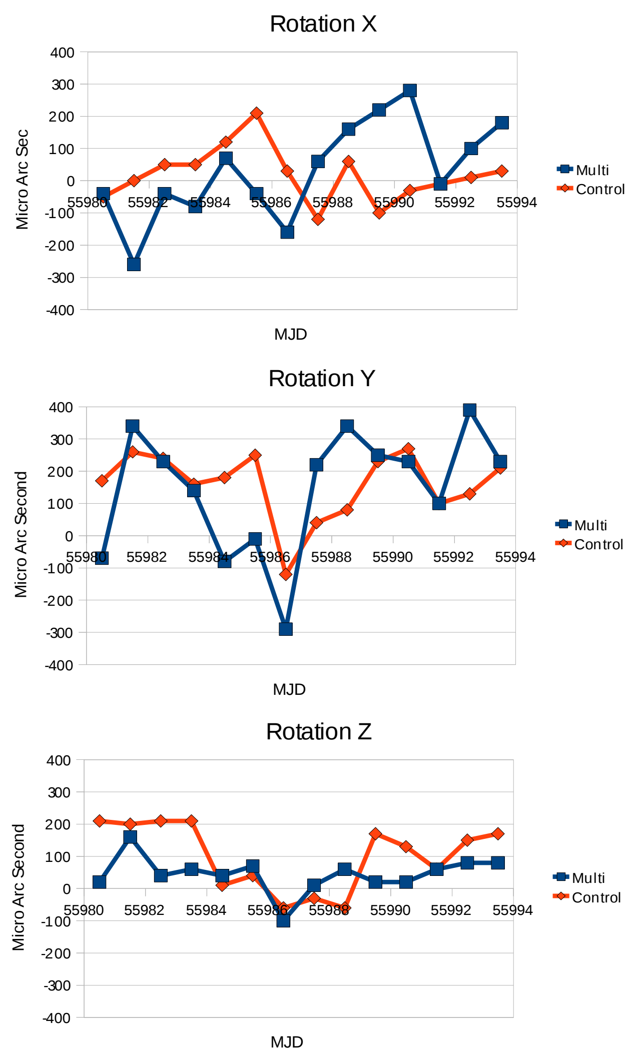

Figure 3. Rotational Values from a 7-Parameter Helmert Transformation for the Multi-GNSS and Control Orbits with Respect to the IGS Rapid Combination Orbit for Days 054-067 of 2011

TABLE IV. MULTI-GNSS SIGNAL AND CONTROL RAPID SOLUTION DIFFERENCE WITH IGS RAPID COMBINATION PRODUCT: EARTH ORIENTATION PARAMETERS FOR DAYS 054-067 OF 2011

		Average [µas]	Std. Dev. [µas]
Multi.	***Polar Motion X***	**-222**	**160**
	Polar Motion Y	**-56**	**144**
Control	***Polar Motion X***	**-188**	**92**
	Polar Motion Y	**3**	**97**

The biggest impact from the incorporation of the GLONASS observations for the polar motion estimates, in Tab. 4, appears to be an increase in the variation. It is clear that some changes to the processing would need to be applied to properly account for the Earth orientation parameter estimates for a multi-GNSS signal solution.

Since the GLONASS satellites have a much higher inclination than the GPS satellites, it is informative to examine the effects of including this new constellation on the individual stations, especially in higher latitudes which receive additional coverage by the GLONASS satellites. It is seen in Tab. 5 that the station coordinate estimates are improved with smaller RMS errors in general. This is a benefit that appears to be propagated through the network of stations regardless of their latitude or if they receive the GLONASS signal. The exact cause of this is yet to be determined, but this result has been seen by Dach et al. [4] with an improvement in Position Dilution of Precision (PDOP) with the inclusion of GLONASS observations as well as by Ineichen et al. [5] who noted the same the effect while analyzing the regional EUREF network.

By inspecting the station repeatability for the multi-GNSS signal and the control coordinate estimates, it can be seen in Tab. 5 that the addition of the GLONASS observations improves the repeatability for most of the stations in all three directions, North (N), East (E), and Up (U). Firstly, this gives an internal quality control check to the multi-GNSS solution indicating that there is good stability of the processing over the 14 days. Secondly, the improvement in all stations is provided by roughly 1/3 of the stations which receive GLONASS observations as well as GPS. Tab. 6 provides a breakdown of the percentage improvements of the RMS values for the stations into geographical groups. Note that the stations within +/-55 deg latitude of the equator show the biggest improvement in their RMS values. However, since this group accounts for the majority of the stations, it is not surprising to see that their percentage of improvement is close to the average for all the stations. The group of 5 stations which lie at the latitudes above +/-55 deg, show improvement but it is important to note that it is skewed by the MAW1 station which is one of the few stations whose position stability is degraded by the inclusion of GLONASS data.

IV. CONCLUSIONS

While the initial results of the multi-GNSS signal processing appear to be promising, especially in the network station coordinate estimation and the Z-direction rotational value, the relatively short 14-day test period may not be completely indicative of the results produced for an ongoing operational processing set up. Therefore, the multi-GNSS signal processing will continue in parallel with the control run as a way to monitor the long-term quality of the solutions.

As for the operational rapid products, they maintain their high level of precision and reliability with respect to IGS for 2011 with 1-3 cm post-processed and ~5 cm RMS predicted for orbit precision and ~125 ps post-processed and 2-3 ns RMS predicted for clock-estimate precision. The polar-motion estimate precision is less than 200 microarcsec post-processed and 350-400 microarcsec predicted in both the X and the Y directions. LOD estimates have 10-20 microsec precision. As noted the rapid Earth orientation parameters and clock time estimates have shown improvement during 2011.

TABLE V. STATION REPEATABILITY FOR THE MULTI-GNSS SIGNAL TEST SOLUTION AND THE CONTROL SOLUTION FOR DAYS 054-067 OF 2011

Stat.	Lat.	GLO	Control			Multi.		
	[deg]	Yes?	*N [mm]*	*E [mm]*	*U [mm]*	*N [mm]*	*E [mm]*	*U [mm]*
MAW1	*-67.6*	*X*	*8.8*	*5.8*	*10.9*	*11.3*	*4.6*	*14.0*
CAS1	*-66.3*	*X*	*9.2*	*5.0*	*12.6*	*8.3*	*6.9*	*12.3*
MAC1	*-54.5*	*X*	*9.6*	*4.2*	*8.3*	*5.6*	*6.2*	*9.0*
LPGS	*-34.9*		*16.8*	*13.1*	*18.4*	*16.2*	*8.2*	*11.3*
ISPA	*-27.1*		*18.4*	*12.5*	*11.9*	*13.0*	*6.6*	*11.8*
HRAO	*-25.9*		*16.6*	*8.3*	*10.0*	*15.7*	*7.7*	*10.2*
UNSA	*-24.7*		*17.3*	*14.3*	*13.2*	*15.6*	*7.9*	*11.0*
CHPI	*-22.7*		*16.8*	*13.8*	*16.2*	*13.9*	*9.3*	*9.1*
THTI	*-17.6*	*X*	*18.9*	*8.6*	*14.7*	*14.0*	*9.0*	*15.6*
ASPA	*-14.3*	*X*	*19.4*	*10.2*	*17.5*	*13.6*	*8.5*	*10.8*
DARW	*-12.8*	*X*	*16.6*	*12.5*	*12.7*	*13.9*	*10.3*	*13.7*
COCO	*-12.2*		*14.7*	*8.8*	*17.1*	*13.1*	*9.0*	*21.7*
NKLG	*0.4*	*X*	*19.1*	*7.4*	*6.2*	*14.8*	*8.1*	*7.7*
GUAM	*13.6*		*15.0*	*10.3*	*14.3*	*10.3*	*8.6*	*16.2*
PIMO	*16.6*		*12.2*	*10.9*	*12.9*	*7.1*	*3.7*	*2.6*
CRO1	*17.8*		*12.8*	*7.2*	*9.4*	*8.3*	*7.3*	*9.1*
KOKB	*22.1*		*13.7*	*8.9*	*8.6*	*6.9*	*8.1*	*5.7*
MAS1	*22.8*	*X*	*14.8*	*7.6*	*9.4*	*9.4*	*8.4*	*8.1*
LHAZ	*29.7*	*X*	*14.3*	*9.0*	*15.8*	*9.3*	*7.7*	*6.4*
DAEJ	*36.4*		*13.3*	*10.3*	*15.3*	*11.4*	*7.4*	*13.1*
AMC2	*38.8*		*10.7*	*8.6*	*10.1*	*7.1*	*4.9*	*7.3*
USNO	*38.9*		*10.8*	*8.5*	*10.7*	*7.5*	*6.1*	*8.9*
USN3	*38.9*		*10.7*	*8.4*	*10.1*	*7.3*	*5.8*	*8.3*
GODE	*39.0*		*10.9*	*8.3*	*10.5*	*7.7*	*5.7*	*8.9*
KIT3	*39.2*		*16.7*	*8.3*	*15.5*	*7.7*	*4.5*	*13.0*
BJFS	*39.6*	*X*	*14.1*	*10.0*	*11.8*	*8.9*	*5.8*	*7.1*
ALGO	*46.0*		*9.8*	*8.4*	*12.3*	*7.2*	*6.7*	*9.2*
DRAO	*49.3*		*10.2*	*8.2*	*14.3*	*7.1*	*5.7*	*9.4*
IRKT	*52.2*		*17.1*	*9.0*	*19.6*	*15.6*	*6.5*	*16.5*
WILL	*52.2*		*7.7*	*6.8*	*14.4*	*4.4*	*5.0*	*9.2*
WSRT	*52.9*		*12.8*	*5.9*	*8.2*	*6.8*	*8.3*	*6.9*
MDVJ	*56.0*	*X*	*13.9*	*7.4*	*12.5*	*7.9*	*6.7*	*11.3*
WHIT	*60.8*	*X*	*9.9*	*7.6*	*15.6*	*7.0*	*5.1*	*8.5*
THU3	*76.5*		*6.5*	*9.8*	*15.7*	*6.0*	*5.5*	*9.9*
Av	**-**	**-**	***13.5***	***9.0***	***12.8***	***10.0***	***6.9***	***10.4***

TABLE VI. IMPROVEMENT IN THE STATION REPEATABILITY FOR THE MUTI-GNSS SIGNAL TEST SOLUTION FROM THE CONTROL SOLUTION

Stat.	# GLO. Stat.	# Stat.	N	E	U
Latitude > +/- 55 deg	*4*	*5*	*16%*	*19%*	*17%*
Latitude < +/- 55 deg	*8*	*29*	*27%*	*23%*	*19%*
Multi-GNSS Receivers	*12*	*12*	*26%*	*8%*	*16%*
All	*12*	*34*	*26%*	*23%*	*19%*

DISCLAIMER

Although some software and models are identified for the purpose of scientific clarity, their use is not an endorsement by the USNO or the Department of the Navy.

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